MAGNETIC OBSERVATIONS DURING THE RECENT DECLINING PHASE OF SOLAR ACTIVITY

Edward J. Smith

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

ABSTRACT

Changes in the heliospheric magnetic field during the recent declining phase in solar activity are reviewed and compared with observations during past sunspot cycles. The stud y is based principall y on data obtained by IMP-8 and Ulysses. The field magnitude is found to have increased during the declining phase until it reached a maximum value of 11 .5nT in ≈ 1991.5, approximately two years after sunspot maximum. The dominant polarity of the field as seen by Ulysses from 1991.8 onward is consistent with the field of the sun's south pole which became negative after a reversal in early 1990. The sector structure disappeared at Ulysses in April 1993 when the latitude of the spacecraft was -300 revealing a low inclination of the heliospheric current sheet. The solar wind structure evident in the magnetic field and plasma measurements shows a decline in the number and effectiveness of Coronal Mass Ejections. A large outburst of solar activity in March 1991 caused 4 CME's and numerous shocks at the location of Ulysses. Following a delay of more than a year, a series of recurrent high speed streams and Corotating Interaction Regions commenced in July 1992 which were observed by IMP-8, Ulysses and Voyager 2. In all these respects, the behavior of the magnetic field mimics that seen in the two earlier sunspot cycles. The comprehensive data set suggests a correlation between /B/ and sunspot number. The major solar cycle variations in the radial component (and magnitude) of the field have been successfully reproduced by a recent model consisting of a tilted solar dipole, whose strength and tilt undergo characteristic changes over the sunspot cycle, and the heliospheric current sheet. The large outbursts of activity in mid-1972, mid-1982 and the first quarter of 1991 may represent a characteristic last "gasp" of solar activity before the sun evolves to a different state. The recurrent high speed streams in 1973, 1984 and 1992 accompany the development of large asymetrical polar coronal holes and the growth in intensity of the polar cap fields. After they endure for about one year, the polar coronal holes recede and the high speed streams are replaced by weaker streams more characteristic of solar minimum.

INTRODUCTION

This article is a review of changes in the heliospheric magnetic field (HMF) during the recent decline in sunspot cycle #22 (1989-1994), Several spacecraft were operational and acquiring data during this interval, In order of distance from the Sun, they were Pioneer Venus Orbiter (PVO), International Cometary Explorer (ICE), Interplanetary Monitoring Platform (IMP-8), Pioneer 10,11 and Voyager 1,2. A major objective is to relate the changes in the HMF to corresponding changes in the solar magnetic field especially the solar dipole. It follows that changes in the HMF at or near 1 AU will be emphasized to the disadvantage of measurements in the outer heliosphere. The latter would involve additional considerations contingent on the evolution of the field with radial distance.

Since direct measurements of the heliospheric magnetic field by spacecraft became a reality, there have been only three sunspot cycles. (Sunspot numbers, SSN, and cycles will be used here as denoting solar activity generally.) Fortunately, there is a significantly longer record of solar ground-

based observations. The combined data indicate that the most significant changes in the solar and heliospheric fields occur during the declining phase of the sunspot/solar activity cycle. These changes arc well documented and consist of (1) a reversal in the sense of the Sun's polar caps accompanied by a reversal in the HMF polarity, (2) a growth in the strength of the Sun's dipole field accompanied by an increase in the HMF strength to a maximum, (3) a decrease in the inclination of the heliospheric current sheet (HCS) from a nearly polar to a nearly equatorial orientation. The use of the word "accompanied" is not intended to imply simultaneity and, in fact, relative phasing and delays between changes in the Sun's field and in the HMF response are of obvious scientific interest.

FIELD MAGNITUDE

Spacecraft observations first became available during sunspot cycle #20 (maximum in Nov. 1968). Little change was seen in field magnitude, B, prompting the general view that perhaps the field did not vary with the solar cycle. A solar cycle dependence was identified at the succeeding sunspot minimum (June, 1976) when B was seen to decrease /1/. The next cycle (maximum in Dec. 1979) produced the first large, obvious increase in B /2/. Maximum B occurred about two years after sunspot maximum, following which the field strength again declined to a minimum in 1986.

During the recent sunspot cycle (maximum in July 1989) reasonably continuous data are available from IMP-8 and Ulysses (October, 1990 onward), the latter traveling between 1 and 5 AU. Measurements by the two spacecraft are shown in Figure 1, the average of B over successive solar rotations (taking account of the differing synodic periods at Earth and Ulysses). The Ulysses values have been extrapolated back to 1 AU (r_o) using the Parker model /3/, i.e.,

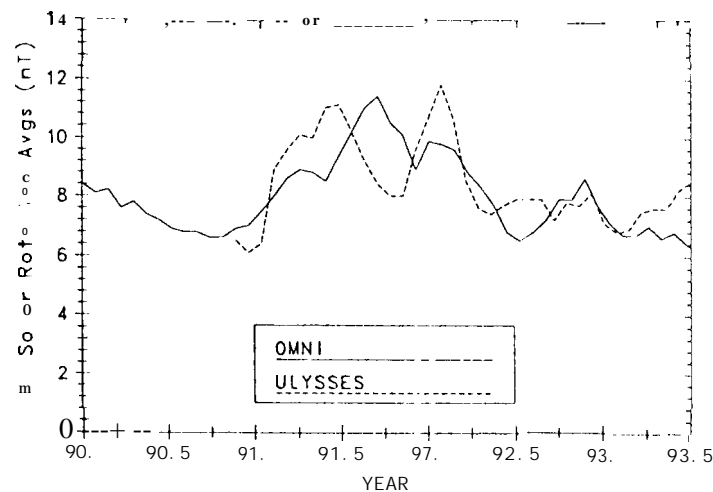$$B(r_0) = 2^{1/2}(r^2 + r^{-4})^{-1/2} B(r), \text{ assuming } \tan \psi = 1.$$

Fig. 1. Field magnitude, B, during recent declining phase. B, averaged over successive solar rotations, is shown over a 4 1/2 year interval. The solid line connects IMP 8 data. The dashed line shows Ulysses measurements obtained from 1 to 5AU extrapolated inward to lAU. The peak value of B ($\approx$ 1 lnT) occurred in mid-1991 approximately 2 years after sunspot maximum.

The two data sets agree in showing a maximum about 1 1/2 years after sunspot maximum but disagree somewhat as to when it actually occurred. The peak appears to occur earlier at Ulysses (1991 .25) than at IMP (1991.75), The difference is probably caused by the large solar events of March 1991. The Ulysses measurements arc not only strongly influenced by these events but use of the Parker model to extrapolate to 1 AU is undoubtedly inappropriate. Although the IMP data suffer

from gaps when the spacecraft was inside the Earth's magnetosphere, they are probably more representative of B. Accordingly, maximum B appears to have occurred in the Fall of 1991.

A retrospective look at the last three solar cycles is now possible. Figure 2 extends previous observations of B into the present along with the (smoothed) sunspot numbers. The times of maxima (M) and minima (m) in solar activity are identified. It now seems clear that B did, in fact, increase in cycle #20 but that the variation was smaller than in the two more recent cycles. As the figure shows, the sunspot numbers were also significantly smaller for cycle #20 than for #21 or #22, suggesting a connection between the two parameters.
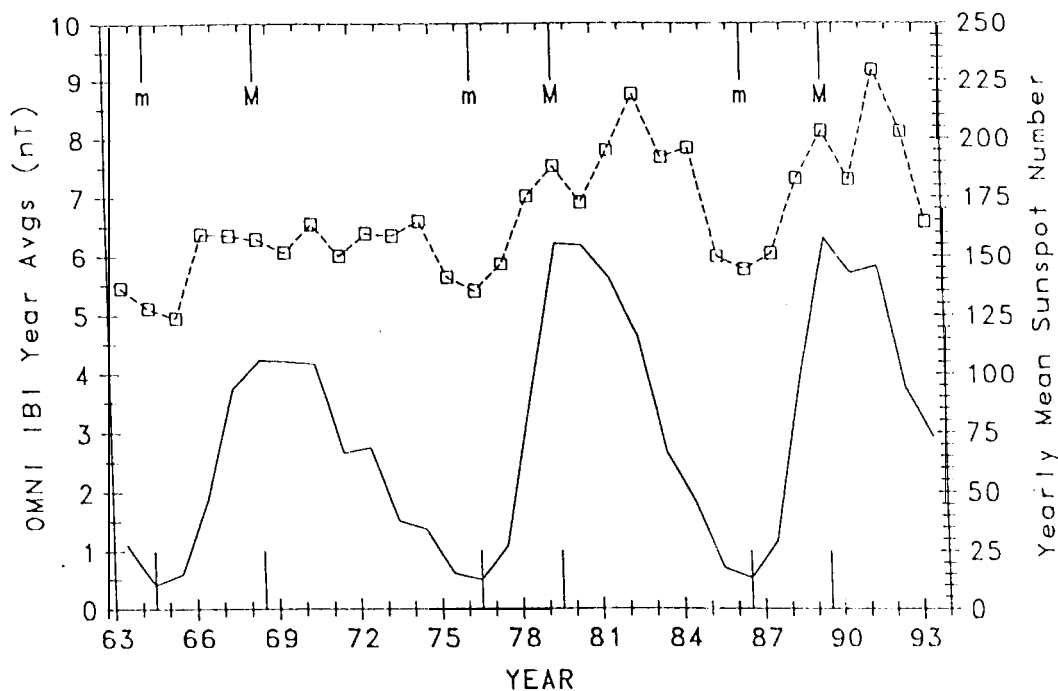

Fig. 2. Field magnitude and sunspot numbers over the last three cycles. Composite measurements (annual averages) of B obtained by many spacecraft over the 30 year interval appear in the upper (dashed) curve (scale to the left). The yearly averages of the sunspot numbers are connected by solid lines (right scale). The two sets of data are well correlated with corresponding minima (m) in B and SSN, maxima (M) in B following maxima in SSN and dips in B near the times of polar cap polarity reversals,

Another feature of the figure is the appearance of secondary minima at about the times of the polarity reversals, Dips in B were observed in 1980 and 1990 and probably in 1970. It is perhaps somewhat surprising that the disappearance of the polar cap fields and their reappearance with the opposite polarity doesn't have a more profound effect on B.

INCLINATION AND POLARITY REVERSAL OF THE HELIOSPHERIC CURRENT SHEET

Initial evidence of a systematic change in the HCS inclination emerged from studies of the dominant polarity, i.e., the fraction of a solar rotation with a positive (or negative) polarity, $P(+) = N(+)/N$, where the number of days having a positive polarity is $N(+)$ and the total number of days is N. Rosenberg and Coleman /4/ found a correlation between $P(-)$ and the heliographic latitude of the observing near-Earth spacecraft. The initial study was subsequently extended to include the interval after 1970 when the Sun's polar caps reversed polarity and the phase relation was also seen to reverse. This study was extended to several earlier solar cycles by Wilcox and Scherrer /5/ who used sector polarities inferred from Earth-based observations of a diurnal variation in polar cap magnetic fields.

A modification of this type of analysis which has worked successfully is correlation of the polarity difference, $\Delta P(+)$, with the latitude difference, $\Delta\delta$, of two observing spacecraft /6/. This approach was applied to the recent decline in sunspot number using IMP-8 and Ulysses (launched a few months after the polarity reversal). The results are not shown because the correlation turned out to be poor. The reason is that the high current sheet inclination reduces the latitude dependence (the signal) while solar activity causes large time variations (noise). This technique is evidently best suited to solar minimum.

The most obvious evidence of the low inclination of the HCS at sunspot minimum and of the polarity above the current sheet have been obtained by spacecraft above *or* below the ecliptic by 15° or *more.* The first observations completely free of the HCS were obtained by Pioneer 11 in 1975-76 at 16° north latitude /7/. For several solar rotations, only a single magnetic sector was observed whose polarity coincided with the outward field in the Sun's north polar cap.

A similar disappearance of the sector structure was seen the following sunspot minimum at $\approx$ 1986.25, again by Pioneer 11 at $\approx$ 16° /8/. The magnetic polarity was now inward again corresponding to that of the Sun's north pole. Both Pioneer 11 observations were the consequence of the decline in HCS inclination. Confirmation is provided by the. source surface contours of the neutral sheet and by the earlier disappearance of the sector structure in late 1985 at Voyager 1 at a higher latitude ($\approx 35°N$) than Pioneer 11 /9/.

During the recent declining phase, in April 1993, the sector structure disappeared at Ulysses then located at 30° South latitude (Figures 3,5) /10/. This occurrence is the third successive sunspot minimum in which the HCS has been confirmed to be at low inclination. Comparisons continue to be carried out in an effort to reconcile the time of the disappearance with the time expected from source surface neutral line contours /1 1/, /12/. Such a comparison is one means of testing the validity of the computed neutral sheet (NS) structure at moderate latitudes.
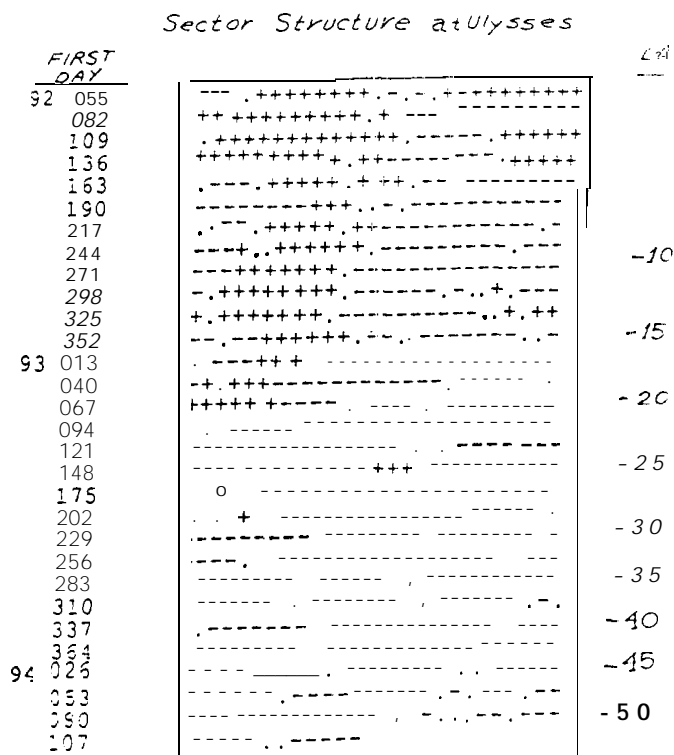
Fig. 3. Sector structure at Ulysses during the recent declining phase. Daily polarities at Ulysses are shown following Jupiter encounter as the spacecraft south latitude increased from -5° to -45°. Ulysses was near aphelion (≈ 5 AU) during this time. The positive sectors disappeared in April 1993 at $\approx$ -30°.

SOLAR WIND STRUCTURE: CORONAL MASS EJECTIONS AND HIGH SPEED COROTATING STREAMS

Parker's model includes both a steady state solar wind and superposed transients, the latter treated in part as "blast waves" /3/, Understanding the steady solar wind, the transients and their mutual interaction has been a persistent theme /13/. The association of the two types of structure with corresponding solar structures has resulted from comparisons of in-situ spacecraft measurements and remote-sensing by coronagraphs and short wavelength telescopes carried above the Earth's atmosphere by other spacecraft. The resulting associations are generally between the high speed streams and coronal holes and between transients, i.e., coronal mass ejections (CMEs), and prominences or helmet streamers.

The appearance of large amplitude recurrent streams enduring for many solar rotations is correlated with the solar cycle, They were first noted in 1973 during the declining phase of cycle #20 and their large change in speed was found to be the most notable variation during the sunspot cycle /14/. (By contrast, the average wind speed varied only slightly.). The streams were also evident in magnetic field measurements, especially at Pioneer 10, 11 beyond 1 AU, where they appeared as high field regions (CIRs) sharply bounded by a pair of shocks /15/. The large recurrent streams were again seen at the next sunspot cycle in 1984-85, i.e., several years after solar maximum. The high speed streams were observed near 1 AU by IMP-8 and in the outer heliosphere by Pioneer 10, 11 and Voyager /16/, /17/,/18/.

During both of these earlier declining phases, pronounced transient events were detected in conjunction with a sequence of major flares and the most intense solar particle outbursts ever recorded. The first of these was associated with the major events of August 1972 which were recorded by Earth-based observatories and a network of spacecraft /19/, /20/. Another major conglomeration of flares, energetic solar particles and magnetic storms occurred in July 1982 /21/, /22/.

The timing of these outbursts of solar activity is such that they preceded the onset of the large corotating streams by 1-2 years. They may represent the "last gasp" of major solar activity and could reflect a major restructuring of solar magnetic fields as the active regions decline and the large polar coronal holes develop.

What occurred during the recent declining phase? The smoothed sunspot numbers peaked in July 1989, However, after a decline of approximately one year, there was a resurgence in SSN and solar activity which produced a secondary peak in March to June 1991, It was in this latter interval that large solar events were observed at Earth, Ulysses and the other heliospheric spacecraft including Pioneer 10, 11 and Voyager.

A good view of the associated CMEs was provided by Ulysses, then at 2,2 AU, by virtue of its nearly continuous data coverage, The Ulysses instruments recorded solar wind transients and large increases in the fluxes of energetic particles (as documented in a special issue of GRL /23/), Four large CMES were discerned in the plasma and magnetic field data between March 5 and April 3 /24/ (Figure 4). The rate of occurrence of shocks rose dramatically with eight shocks being identified in the same interval.

The solar wind structure before these events was not markedly periodic but was reminiscent of the weak streams often seen near solar maximum. After the events, however, quasi-periodic streams persisted for the next year although there was an evolution in structure and the periodicity was not clock-like.
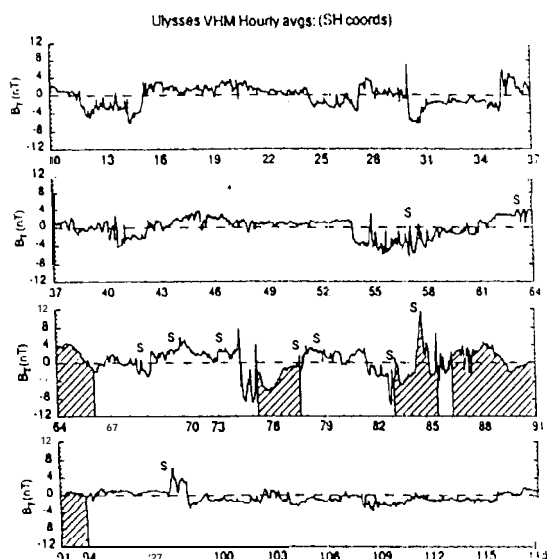
Fig. 4. Effect of CMES *on* the magnetic field in the first third of 1991. The response of the azimuthal field component, BT, to the large solar events of March is shown by the large number of shocks (designated by S) and four CMEs (cross-hatched areas) identified by the Ulysses solar wind instrument. This component also shows the (variable) sector structure.

In July 1992, a sequence of large corotating, clock-like streams began with speeds which varied between 400 and 800 km/s /25/ (Figure 5). Initially, four separate streams and CIRs were identifiable at Ulysses, three having a negative polarity and one, a positive polarity. The variations were no doubt temporal because the high speed streams were also seen at IMP and Voyager 2.

Since Ulysses was then traveling southward at a rate of $==10°$ per month, a latitude dependence also became evident. The lowest speeds gradually rose as the sector structure vanished, a result consistent with the characteristic influence of the HCS, i.e., slow wind near the current sheet and fast wind away from it, After the final HCS crossing, a negative polarity (that of the south solar hemisphere) was persistently seen, low speed wind gradually disappeared and the wind speed approached a steady value of ≈ 750 km/s. Ulysses was continuously inside flow from the south polar coronal hole /11/.
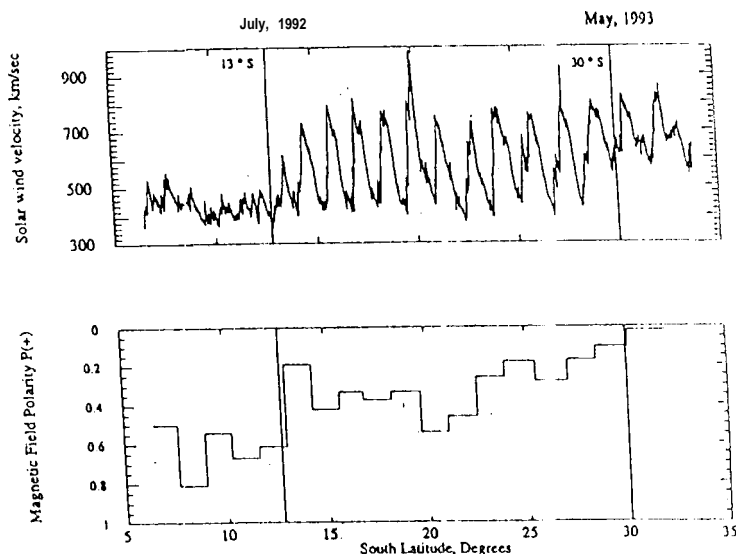

Fig. 5. Large amplitude corotating solar wind streams and dominant polarity. The upper curve is the solar wind speed which reaches maxima of 700-800 km/s. The occurrence of these high speed streams at this time is a solar cycle effect. The gradual disappearance of slow solar wind and of positive polarity fields (lower panel) is a latitude effect . The two vertical lines designate the onset of the high speed recurrent streams and the disappearance of the sector structure.

DISCUSSION

To understand the field changes that take place during the declining phase, they need to be viewed in the context of changes over the solar cycle. Observed changes in the sector structure imply a correspondence between the HMF and the solar magnetic dipole. The polarity above and below the HCS is the same as that of the corresponding polar cap field. When the polar caps reverse polarity, the polarities above and below the HCS also change sign. A close correspondence of this kind has been widely accepted as consistent with the largest scale solar dipole field dominating the coronal field at the high altitudes at which the solar wind originates.

It has also been customary to associate the changing inclinations of the HCS and the sun's dipole. The solar cycle variation of the HCS inclination is well established by mutually consistent spacecraft and Earth-based observations as well as source surface contours. Indirect evidence of the dipole tilt is supplied, for example, by the asymmetric displacement of polar coronal holes from the sun's rotation axis. It is therefore natural to associate the normal to the current sheet with the orientation of the sun's magnetic dipole.

However, an apparent contradiction to this association appears near sunspot maximum. When the sun's axial dipole disappears, B is largely unaffected, This fact implies that, at this time, the solar wind and HMF do not originate from the polar caps. The persistence of the sector structure and the nearly polar orientation of the HCS (and source surface neutral line) are consistent with an equatorial dipole. This realization led to the suggestion that the sun's dipole simply rotates through the equator to the opposite pole /26/. Although the reality of a rotating solar dipole is questionable on the basis of our (limited) understanding of magnetic dynamos, source surface calculations covering solar maximum show that, in effect, that is how the source of the HMF is behaving. It is thought that as the axial dipole wanes, the equatorial dipole component is becoming stronger as the toroidal fields in active regions grow in number and strength.

Source surface calculations reproduce the expected solar cycle variations of the axial dipole (the leading term in the spherical harmonic expansion of the potential fields occupying the shell between the photosphere and the spherical source surface). The model (Figure 6) indicates that the axial dipole moment gradually decreases to zero while its latitude goes to zero (the tilt angle grows to 90°) /27/. The reappearance of the dipole is associated with a change in sign of the latitude angle corresponding to the polarity reversal. The times at which these changes occur are well defined.
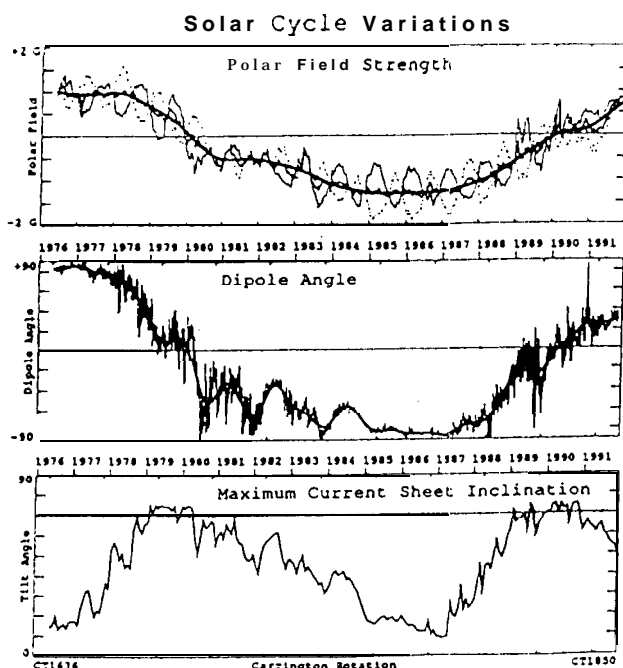

Fig. 6. Solar cycle variations of the polar dipole (from I28I). The upper panel shows the measured field strength in the polar cap. Annual variations in the north and south polar fields occur as the heliographic latitude of Earth changes between ± 7 1/4°. The heavy solid line is the north-south average. The middle panel is the latitude angle of the dipole derived from the spherical harmonic description of the coronal field resulting from the source surface model, The bottom panel contains the psuedo-inclination of the neutral line (HCS) derived from its maximum extent in heliolatitude.

However, to account for the solar cycle variations in the HMF strength, it has proven necessary to add two other sources to the currents on the source surface /28/. The heliospheric current sheet produces a significant field which, for the simplest current sheet configuration corresponding to Parker's model, is radial throughout the heliosphere and is independent of latitude /29/. The other source, as discussed above, is a horizontal or equatorial dipole whose moment is derived from the leading non-axial spherical harmonic terms in the expansion for the source surface field /30/.

A close correspondence has been achieved between spacecraft observations and a model consisting of a tilted solar dipole and the HCS. Wang /30/ has developed an equation for the magnitude of the radial field component in the heliosphere which is expressed (in a slightly different form here) as follows:

$$(1 \, Br(r,\theta)|) = Bp(rs/r)^2 \, [c + d \mid \cos\alpha\cos\theta + 2\sin\alpha\sin\theta/\pi \, 1]$$

The strength of the dipole field at the magnetic pole on the source surface is B_p. The tilt angle (colatitude) of the dipole is α. The radial distance, co-latitude and longitude of the point of observation are r, θ and ϕ. The radius of the source surface is r_s, nominally 2.5 solar radii. The factor, $(r_s/r)^2$, expresses conservation of magnetic flux. The absence of a term involving ϕ is the result of having averaged over a solar rotation.

The remaining two parameters represent the fraction of the magnetic field lines which are "open", i.e., reach the source surface. The parameter, c, refers to the current sheet and parameter, d, to the dipole. Using B_p and a derived from the spherical harmonics and c = 0.6, d = 0.4, Wang was able to achieve a good correlation with the observed /B_r/ including rapid variations that occur on the scale of months (Figure 7), (A somewhat better correlation is obtained by including the higher order multiples from the expansion.) Implicit in the equation is the latitude variation of the field. However, in modeling the observed solar cycle changes in /B_r/, only the field in the ecliptic at lAU is relevant ($\theta = \pi/2$).

By considering the variations in B_p and a, the variations in /B_r/ can be understood. At solar maximum, B_p is essentially the field of the equatorial dipole and a = n/2. Although the dipole moment is not as large as at other phases of the cycle, it is seen in the ecliptic "head-on" and thereby produces a relatively large /B_r/. As the sun rotates, two sectors corresponding to the two magnetic poles will be seen. The HCS also makes a contribution which is proportional to Bp.
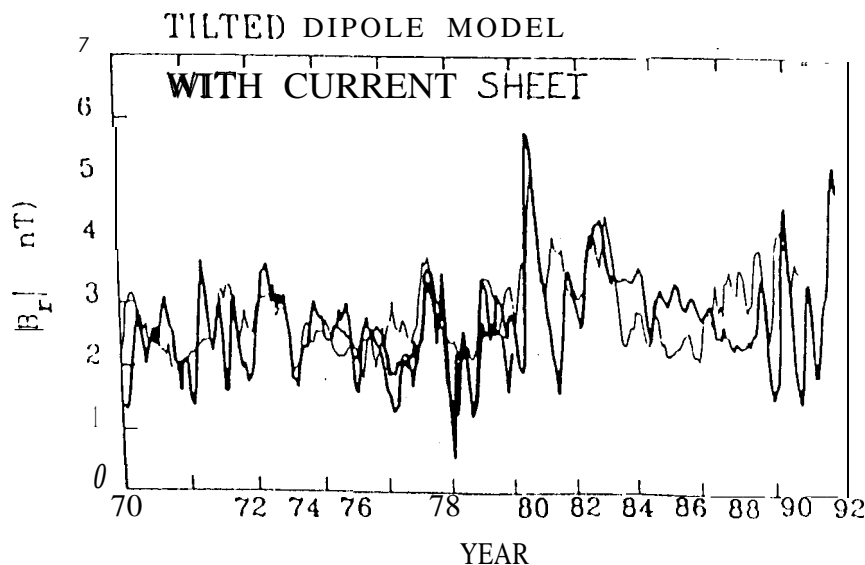

Fig. 7. Comparison of observed and model IBrl (from 1311). The thin line shows three-solar-rotation averages of IBrl measured in the ecliptic at 1 AU by various spacecraft. The thick line is obtained from the equation given in the text corresponding to the fields of a tilted dipole and the HCS.

The maximum in $/B_r/$ occurs during the declining phase as the polar dipole builds-up and the horizontal dipole wanes. The axial dipole and Bp increase in strength until solar minimum. However, $/B/$ is also influenced by the decrease in *a* which tends to compensate for the increase in B_p. A "crossover" occurs such that the maximum in $/B/$ lies between sunspot maximum and sunspot minimum. Near sunspot minimum, the small tilt angle of the dipole virtually eliminates its contribution leaving only the field equivalent to the HCS.

Finally, a few words are in order concerning the changes that take place in the solar wind structure. CMES and fast streams originate in different magnetic structures. CMES originate on closed field loops that frequently take the form of either prominences or helmet streamers /31/ . It is not surprising, therefore, that CMES are prominent near solar maximum when the sun contains large numbers of active regions and regions of evolving flux which represent strong closed fields. The processes of magnetic reconnection that launch the CMES, the forces which accelerate them outward and their internal structure are the subjects of on-going research but their rate of production is clearly favored by an active sun, Regions which produce intense flares and energetic particles also give rise to the largest CMES (although which is cause and which is effect is debatable).

Fast streams originate from open field regions, principally coronal holes, The relation between solar wind speed and the characteristics of the coronal hole is uncertain. A correlation between the area of the hole and solar wind speed has been advocated, The location of the hole with respect to the solar equator may be a factor, i.e., in-ecliptic solar wind comes from the equatorial region of holes. A more recent suggestion is that the rate of expansion with altitude of flux tubes containing open field lines is inversely related to the speed /32/ . The first two concepts are consistent with a correspondence between the large polar coronal holes which reach down to the equator and the large high speed streams. The model based on flux tube expansion can also account for the high speed streams if, as proposed, the expansion is least near the boundary of the polar coronal holes /33/ .

The large streams appear as the polar cap field is growing in strength. The appearance of the large coronal holes indicates a marked increase in the area of the polar caps. However, the finite interval during which the high speed streams are observed argues for a subsequent basic change in magnetic field structure. It is, in fact, observed that, as the dipole inclination becomes more polar, the coronal holes retreat poleward and no longer reach down to the equator.

FINAL COMMENTS

Only good fortune has enabled us to continue our coverage of solar cycle variations. The continuity of the solar wind measurements would have been irreparably broken without the data from IMP-8 which was launched over 20 years ago in 1973. The only other spacecraft in the inner heliosphere, PVO and ICE, have continued to operate but with significant data gaps.

The magnetic field observations during the recent cycle have been supplemented by an improved theoretical understanding, A significant advance was the realization of the important contribution being made by the heliospheric current sheet.

The other major improvement has come from studying the role of the solar magnetic dipole and it's changes. In this regard, field modeling based on the use of a spherical source surface has continued to be useful in spite of the lack of a sound physical basis. (Ian Axford has questioned the physical reality of the source surface and has characterized it as a book keeping arrangement to keep track of open and closed field lines.) An important contribution has been made by Y.M. Wang who introduced a relatively simple phenomenological model based on the fields of the solar dipole and the heliospheric current sheet. The model is able to account for major aspects of the solar cycle variation in the HMF.

One of the goals of the source surface models is to predict the dependence of the HMF on latitude, The inspiration for such an attempt comes from the Ulysses out-of-ecliptic mission which is presently

returning the first ever observations of the sun's polar caps. A number of efforts arc now under way to improve the models and predictions for comparison with the Ulysses magnetic field measurements. Obviously, such comparisons have the potential to improve significantly our understanding of the ongins of the HMF and its time variations.

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